Overview of R7 / Risk-Informed Safety Margin Characterization

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Light Water Reactor Sustainability R&D Program

Outline

- Background Comments:
  - Dynamic PRA, Passive System Functional Reliability, Last 10 years' work on "margins"
- What we mean by "Margin"
- R7 Development Within the Risk-Informed Safety Margin Characterization (RISMC) Pathway of the Light Water Reactor Sustainability Program
- The Collaboration
  - Lab / Academic Partners
  - EPRI
- Path Forward

Background Comments

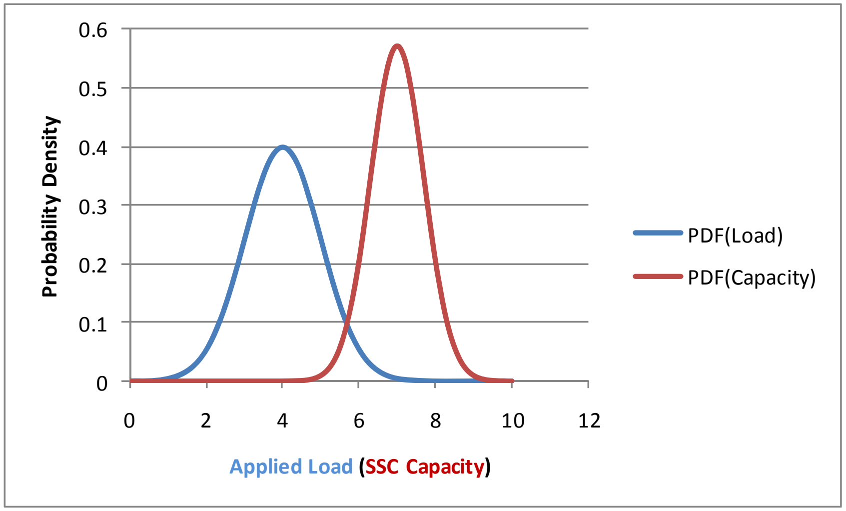
- There has been a lot of relevant work in the last 30 years, integrating Human Reliability Analysis, epistemic and aleatory uncertainty, phenomenology, and so on
  - Dynamic PRA
  - Passive System Functional Reliability
  - Last 10 years' work on "margins": USNRC-sponsored work, CSNI, SM2A, …
- While trying to break new ground methodologically, much of this work tried to use legacy codes
- The work described here is intended to support sustainability decision-making by:
  - Integrating the above-mentioned elements into the analysis, along with:
    - Passive component behavior, effects of off-normal but not necessarily immediate core damage scenarios, ...
  - Developing a modern tool (R7) to better support this kind of analysis

Margin

"Margin" is about P(Load<Capacity). Therefore,

- It's not enough to try to characterize margin JUST by a distance between designated points (e.g., mean values, designated percentiles) of load and capacity pdf's
- One must also say something about uncertainties in L and C…
- … and try to quantify P(L>C)
- *Develop engineering insight into conditions under which failure will occur: i.e., L>C*

"The Logo:"
Basis for quantifying P(L>C)



L: "Load"
C: "Capacity"

Less-Than-Abundant Margin

Abundant Margin

Increasing "Margin"

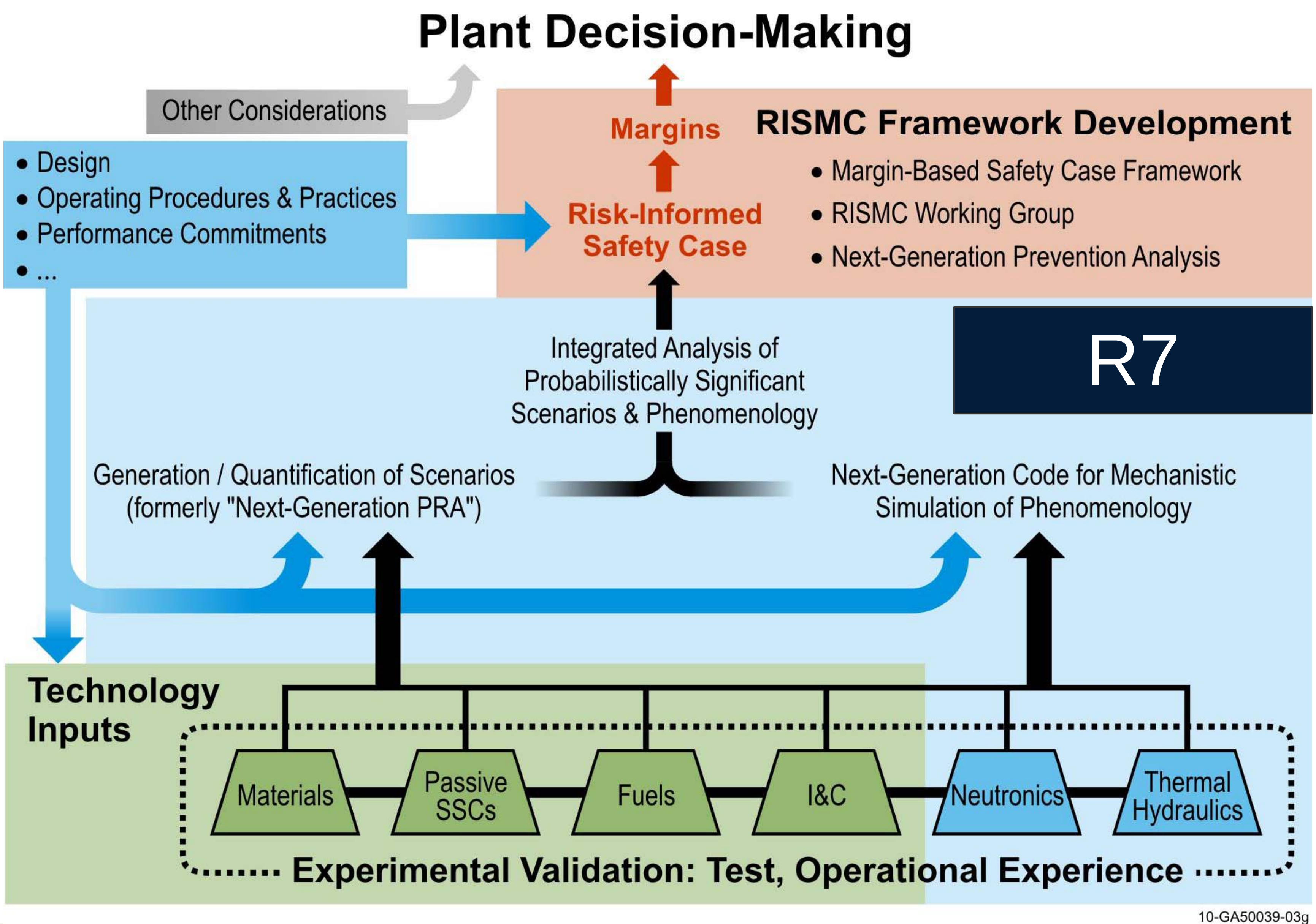
P(L>C | Hardware Success) ~ P(Hardware Failure)

P(L>C | Hardware Success) ?? < P(Hardware Failure)

P(L>C | Hardware Success) << P(Hardware Failure)

Should Quantify

Light Water Reactor Sustainability



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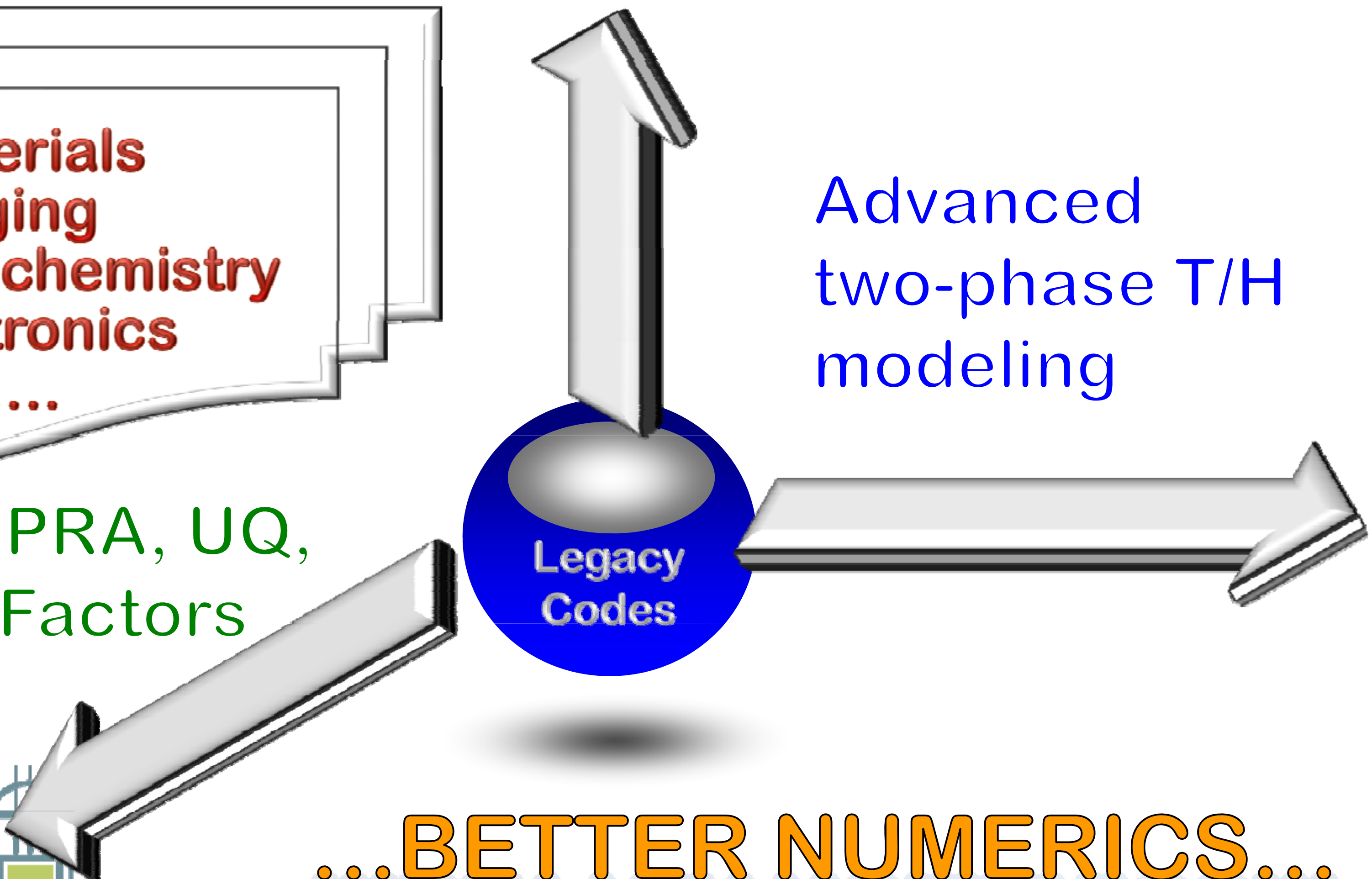
R7 R&D Thrust Directions

SYSTEMS CODE

3D CFD/CG modeling

Materials
Aging
Coolant chemistry
Neutronics
....



Advanced two-phase T/H modeling

RISMC, PRA, UQ, Human Factors

...BETTER NUMERICS...

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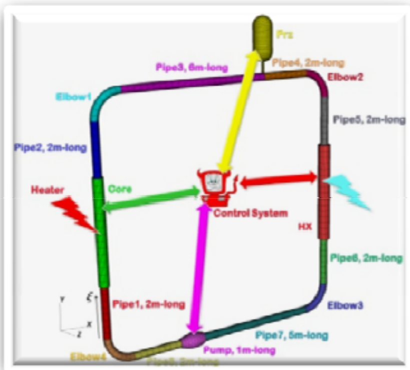
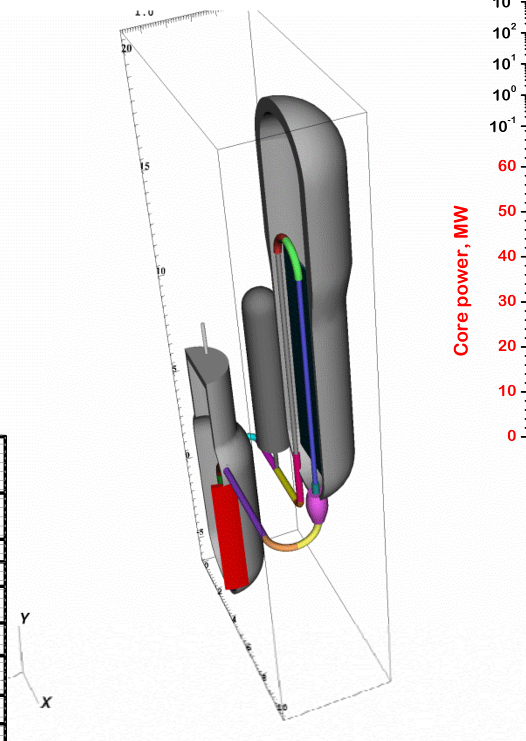
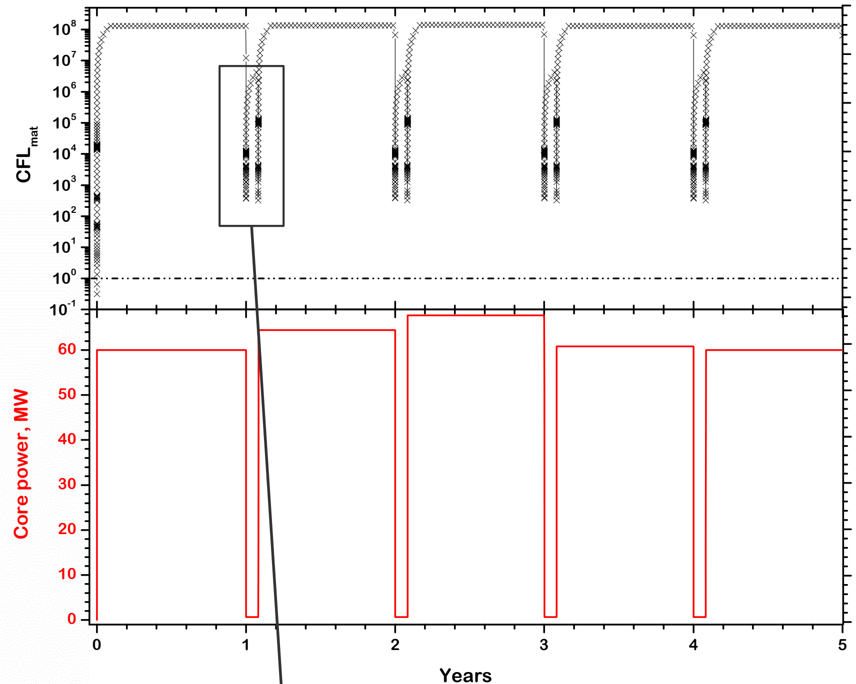
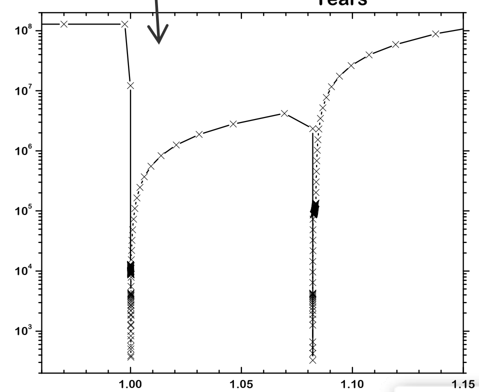
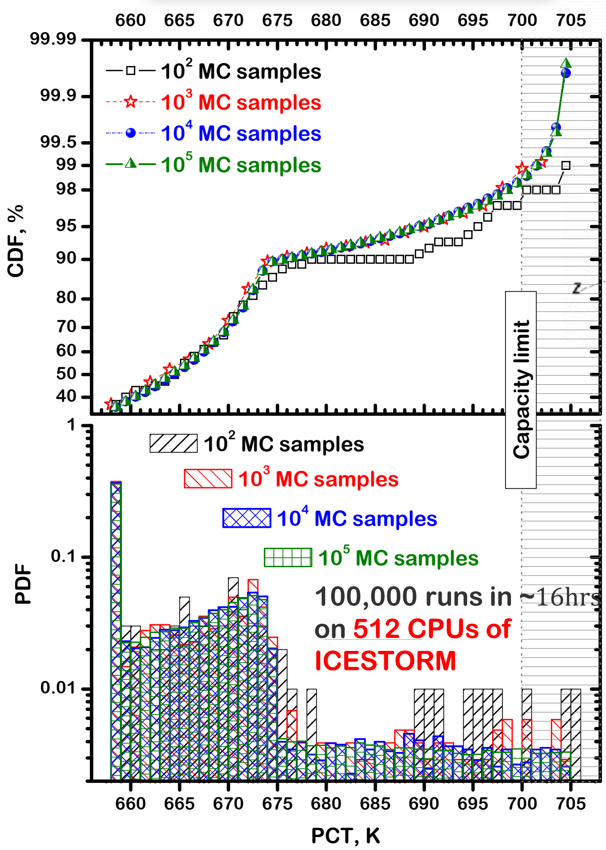
The State of RISMC / R7

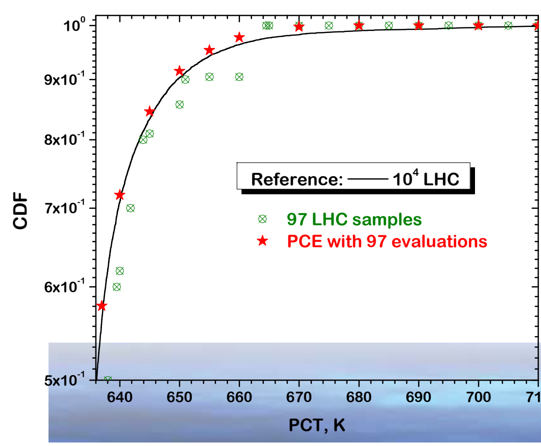


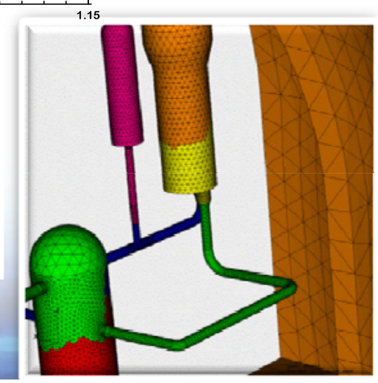




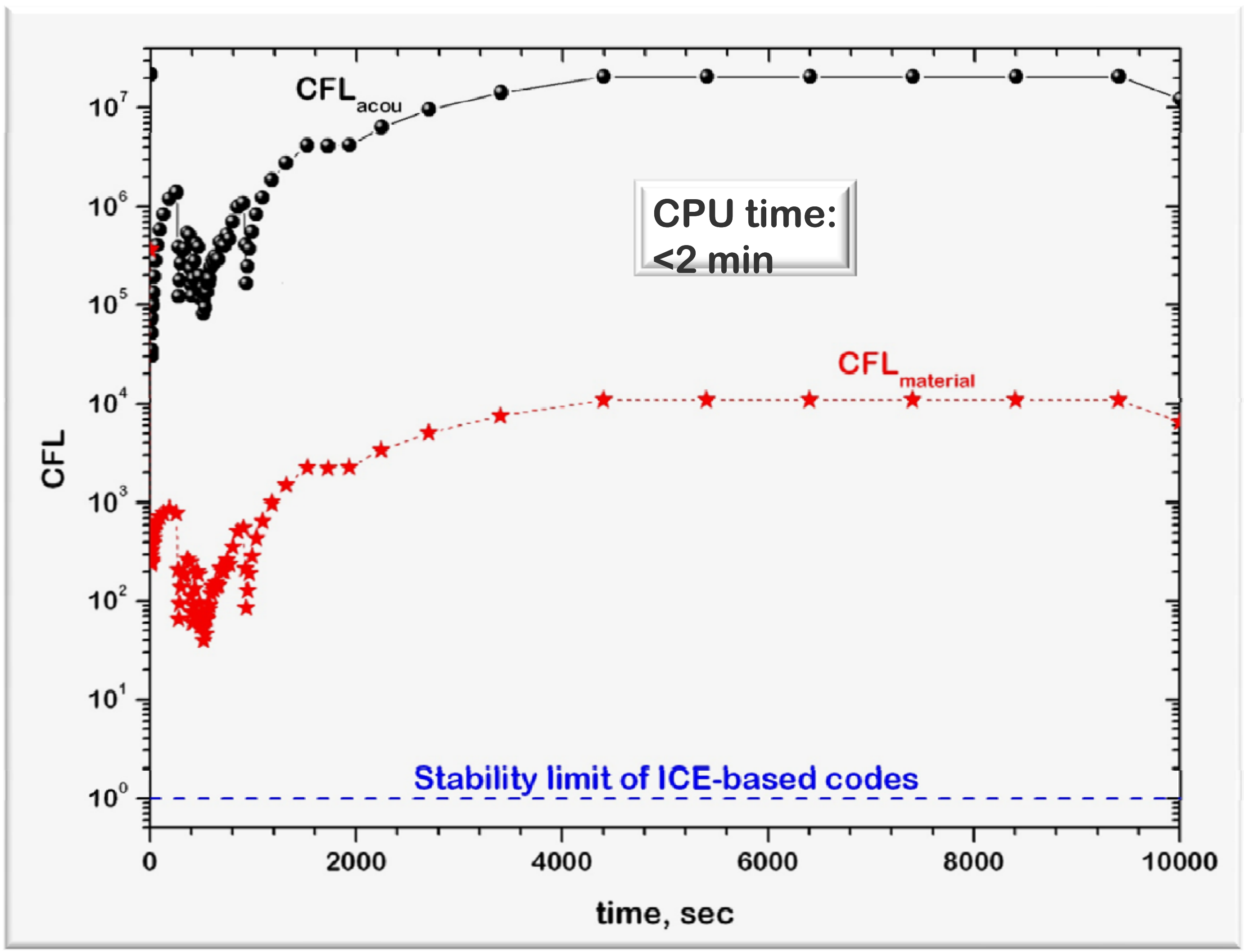








RISMC demo



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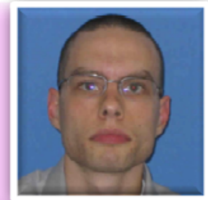
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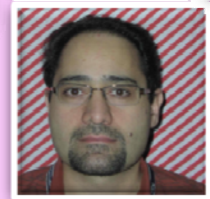
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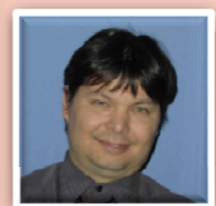
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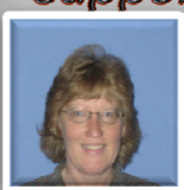
IT: CS, HPC, I/O, GUI support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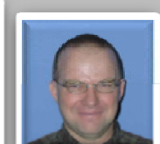

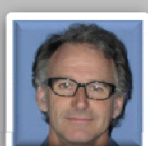

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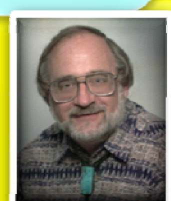
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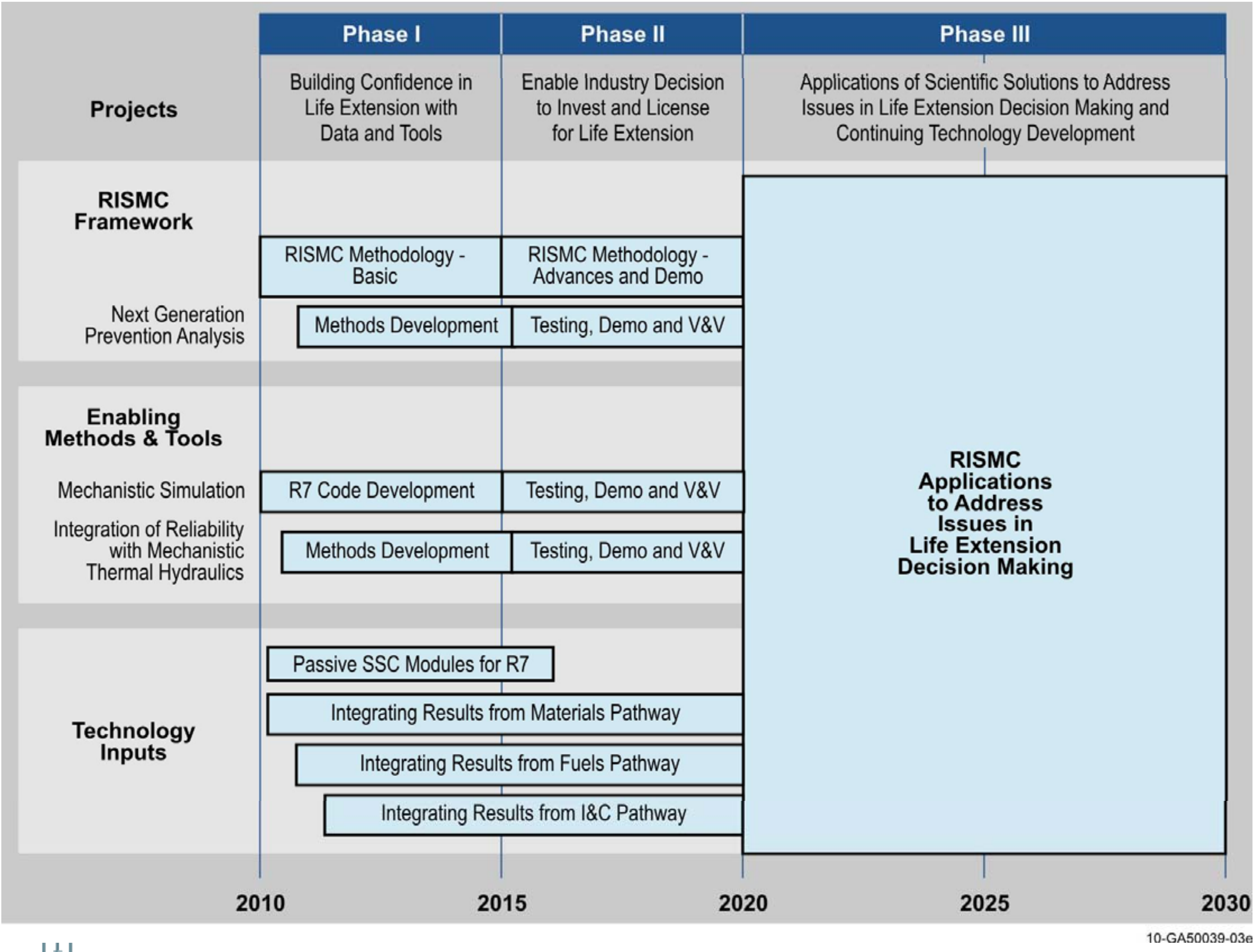
Active Collaboration with Electric Power Research Institute (EPRI)

- Key input into formulation of “use cases” to steer R7
- Collaboration on case studies to sharpen formulation of / illustrate the “logo” framework
- Examples:
  1. Selection of “feed and bleed” as an intermediate-term objective for R7 development
  2. EPRI 1021085 – Desired Characteristics for Next Generation Integrated Nuclear Safety Analysis Methods and Software / Stephen M. Hess / Senior Project Manager / Risk and Safety Management
  3. Pending R7 availability for realistic feed-and-bleed analysis: refine and illustrate the “logo” framework using MAAP as a surrogate for R7 (EPRI-led)
  4. ANS panels & papers (e.g., Hess, Youngblood, and Vasseur: “Recent Trends in Risk Informed Safety Margin Characterization”)

Time Line



Phase I
Phase II
Phase III
Projects
Building Confidence in Life Extension with Data and Tools
Enable Industry Decision to Invest and License for Life Extension
Applications of Scientific Solutions to Address Issues in Life Extension Decision Making and Continuing Technology Development
RISMC Framework
RISMC Methodology - Basic
RISMC Methodology - Advances and Demo
Next Generation Prevention Analysis
Methods Development
Testing, Demo and V&V
Enabling Methods & Tools
Mechanistic Simulation
R7 Code Development
Testing, Demo and V&V
Integration of Reliability with Mechanistic Thermal Hydraulics
Methods Development
Testing, Demo and V&V
RISMC Applications to Address Issues in Life Extension Decision Making
Technology Inputs
Passive SSC Modules for R7
Integrating Results from Materials Pathway
Integrating Results from Fuels Pathway
Integrating Results from I&C Pathway
2010
2015
2020
2025
2030
10-GA50039-03e

Summary

- R7 is being developed as a modern *systems* code
  - Improved modeling and numerics
  - Address sustainability issues
    - Including DBA type scenarios
    - Scenarios that threaten the plant, if not the public
    - Address other plant safety issues
  - Address uncertainty from the beginning: “Do the Logo”
    - In-line modeling of aleatory uncertainty (reliability issues)
    - Close coupling to tools like Dakota for epistemic uncertainty
  - *Develop engineering insight into the conditions under which failure will occur (i.e., L>C)*
- The development is “use-case-driven” and closely coordinated with EPRI and EPRI contractors

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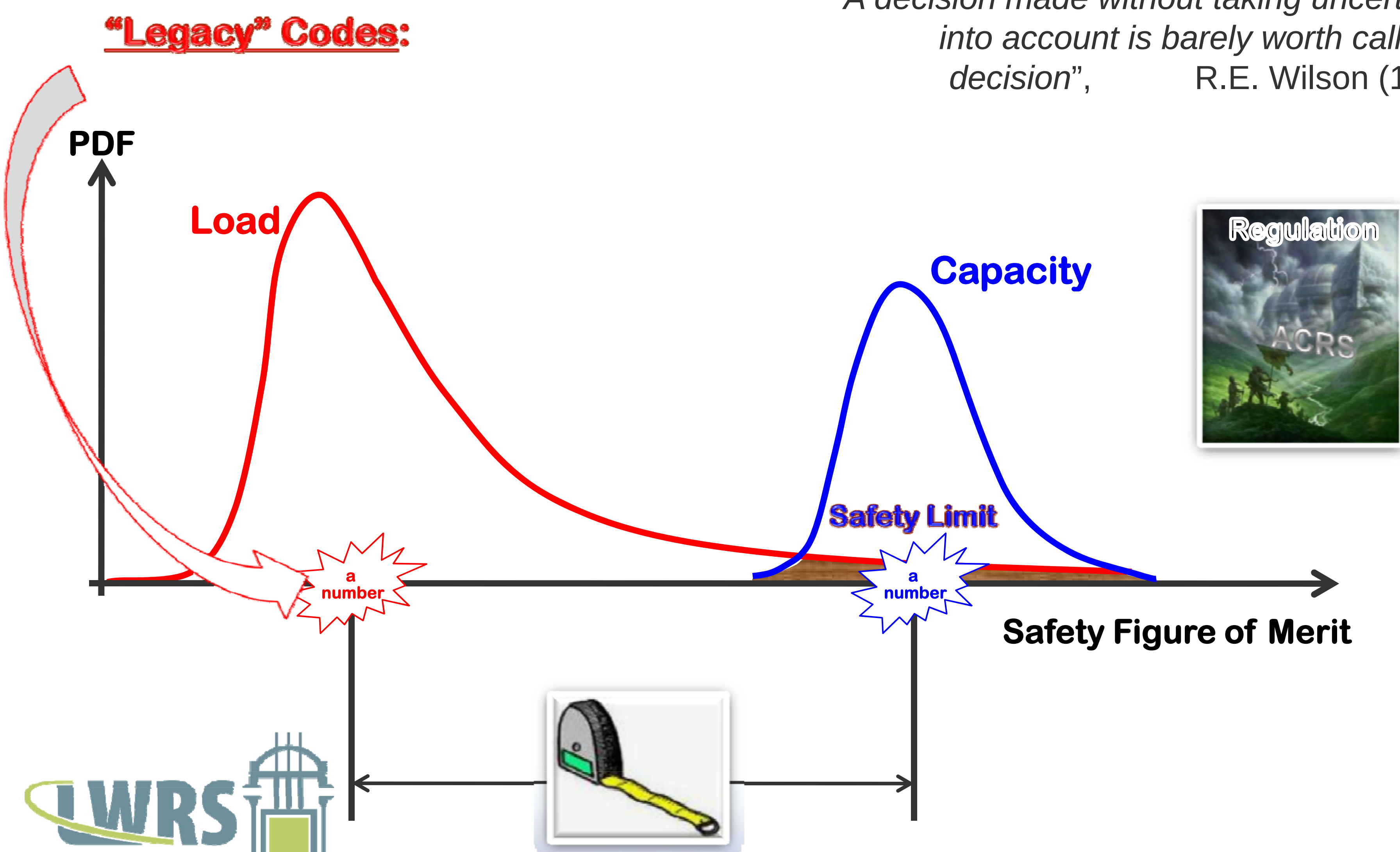
BACKUP

Nuclear Reactor Safety

"A decision made without taking uncertainty into account is barely worth calling a decision", R.E. Wilson (1985)



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Damage Mechanisms – 1/2

	Other disciplines (beside materials science)	Time scales
Embrittlement	Core neutronics Fluid (mixing) Heat transfer Structural mechanics	Long (fluence) Short (thermal shock)
Thermal fatigue (striping)	Fluid flow Heat transfer	Long (accumulation) Short (oscillation)
Structural fatigue (vibration)	Fluid flow Structural mechanics (FSI)	Long (accumulation) Short (oscillation)

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Damage Mechanisms – 2/2

	Other disciplines (beside materials science)	Time scales
Flow-Accelerated Corrosion	Coolant chemistry Fluid flow	Long (accumulation)
Stress Corrosion Cracking (SCC)	Coolant chemistry Fluid flow	Long (accumulation)
Irradiation-Assisted Stress Corrosion Cracking (IASCC)	Neutronics Radiation chemistry (+ CC) Fluid flow	Long (accumulation)

Other damage mechanisms:

Erosion Corrosion, Liquid Droplet Impingement-Induced Corrosion, Cavitation Corrosion, Environmentally Assisted SCC

Modeling of Plant Aging

Objective: Capture vulnerability hidden under four modes of negative synergy (non-intuitive / no-”prior” nonlinearity).

1. Synergy of physics: neutronics, fluid flow, heat transfer, structural mechanics, coolant / radiation chemistry
2. Synergy of multiple damage mechanisms (accelerated degradation)
3. Synergy of safety threats (i.e. addition of fire, flooding, earthquake challenge) on already weakened SSCs
4. Synergy between aging / degraded materials and aging / obsolete procedures, training, I&C, surveillance and diagnostics strategies

Approach to Modeling of Plant Aging

Task: Compute Loading and Compute Capacity on sensitive SSCs

1. Multi-physics (needed for each damage mechanism)

2. Comprehensive coverage of different damage mechanisms

3. Amenable for (future) integrated treatment of safety threats

4. Address plant complexity in its totality (e.g. by including effect of I&C, operating procedures, operator actions, S&M)

Computational Challenges

Multi-Physics Integration:

- CN, TH … + SM, CC + damage / degradation models

Multi-Scale Integration:

- Need for "gap-tooth" scheme …. to zoom in to capture
  - -- rates of damage growth under high-frequency stressors;
  - -- accelerated damage growth in "shock" events.
- Need high fidelity (e.g. 3D CFD in the vicinity of sensitive SSCs) to capture the delicate stressors → 0D/1D/3D transitions

Code Calibration:

- Incomplete historical data to reconstruct "plant health"

Vulnerability Search:

- Need effective sampling strategies to overcome local minima.

Elements of the Strategy

Risk-Informed Safety Margin Characterization (RISMC) Methodology

Next Generation System Safety (R7) Code

Reactor Safety Research & Testing (V&V) Infrastructure

R7 R&D

Broad Stakeholders and Support Base

I-NEST CORE
"Safety & Licensing"

"Modeling, Experimentation, and Validation" (MeV) Schools

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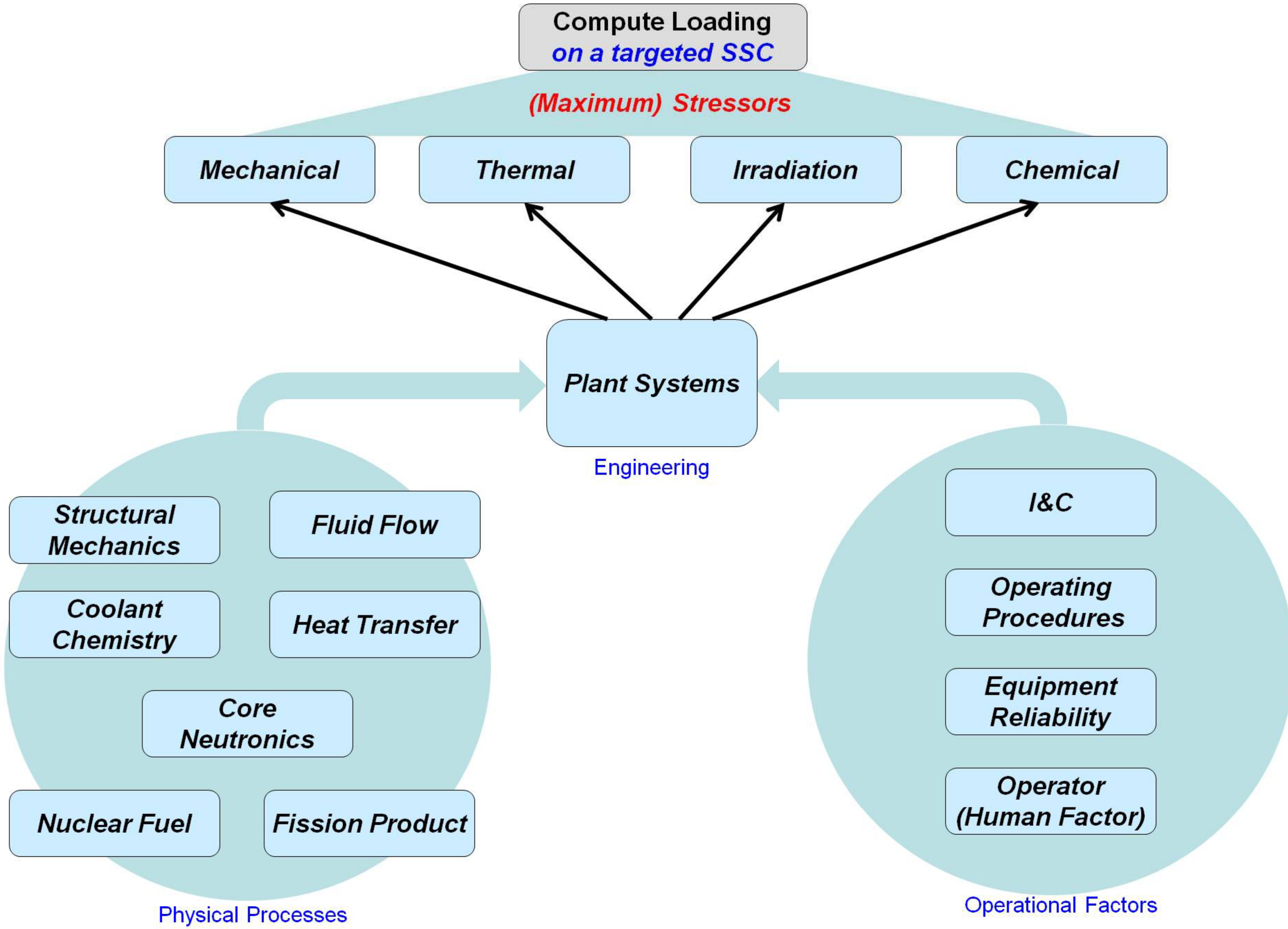
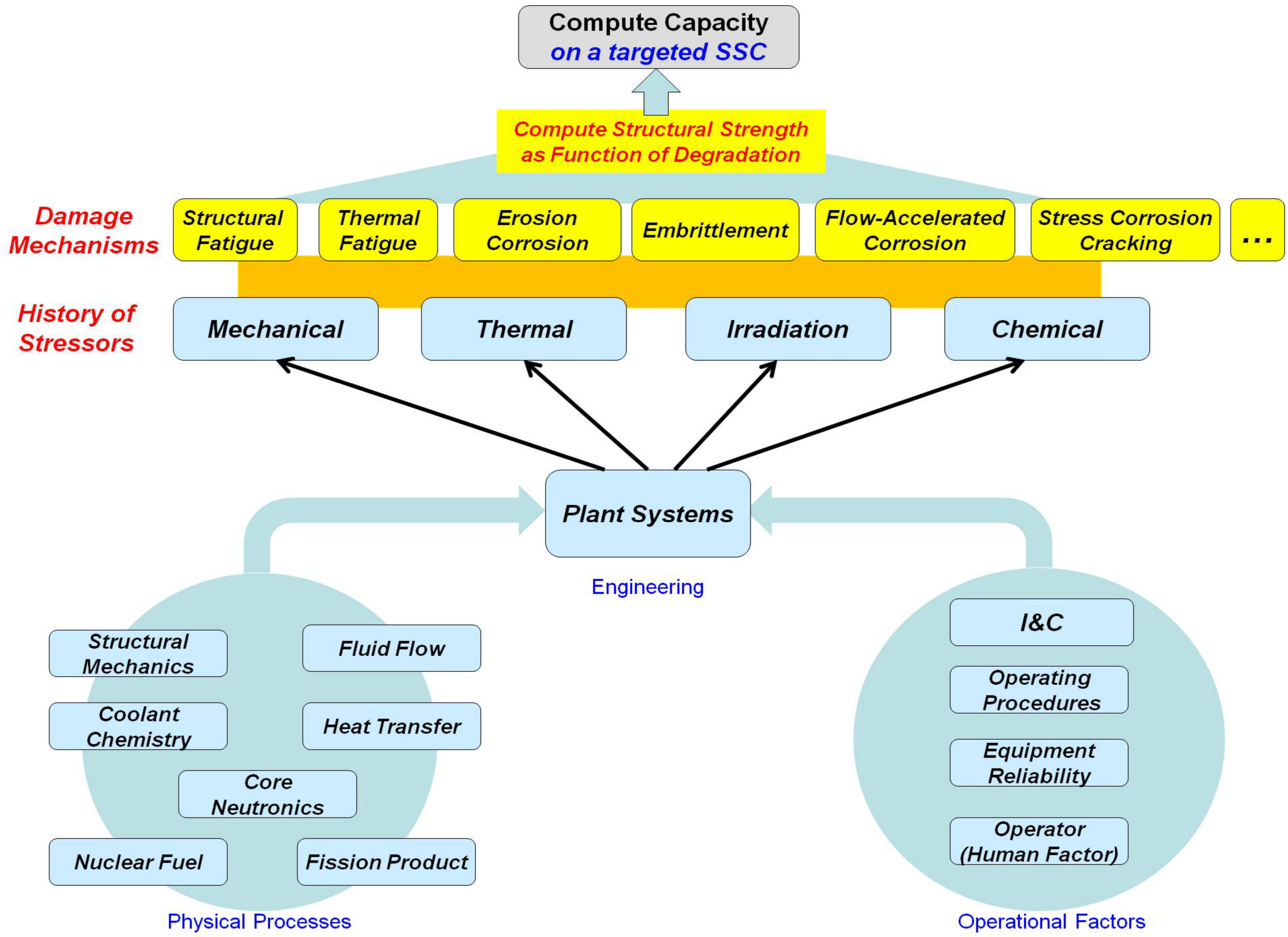

Compute Loading
on a targeted SSC
(Maximum) Stressors
Mechanical
Thermal
Irradiation
Chemical
Plant Systems
Engineering
Structural Mechanics
Fluid Flow
Coolant Chemistry
Heat Transfer
Core Neutronics
Nuclear Fuel
Fission Product
Physical Processes
I&C
Operating Procedures
Equipment Reliability
Operator (Human Factor)
Operational Factors

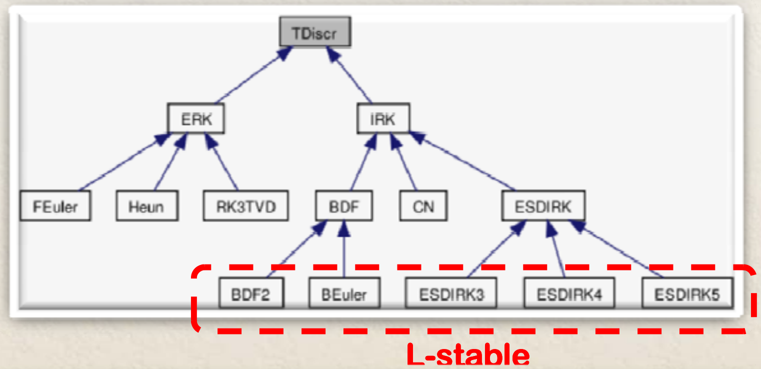

Compute Capacity
on a targeted SSC
Compute Structural Strength
as Function of Degradation
Damage Mechanisms
Structural Fatigue
Thermal Fatigue
Erosion Corrosion
Embrittlement
Flow-Accelerated Corrosion
Stress Corrosion Cracking
...
History of Stressors
Mechanical
Thermal
Irradiation
Chemical
Plant Systems
Engineering
Structural Mechanics
Fluid Flow
Coolant Chemistry
Heat Transfer
Core Neutronics
Nuclear Fuel
Fission Product
Physical Processes
I&C
Operating Procedures
Equipment Reliability
Operator (Human Factor)
Operational Factors

Version β-2: highlights

- Object-oriented (C++)
- Parallel (MPICH)
- High-order in space
- Fully-implicit, L-stable, High-order in time
- State-of-the-art linear algebra (Krylov-based, JFNK, PETSc)
- All-speed capabilities, t/d consistent real fluid EOSs
- Advanced 2-phase flow modeling
- CFD capabilities
- Neutronics: nodal diffusion
- Uncertainty Quantification enabled (integration with DAKOTA)

Recovery DG (1D)
(up to 12th-order)

Reconstructed DG
(2D & 3D unstructured-grid)
(3rd-order and higher)



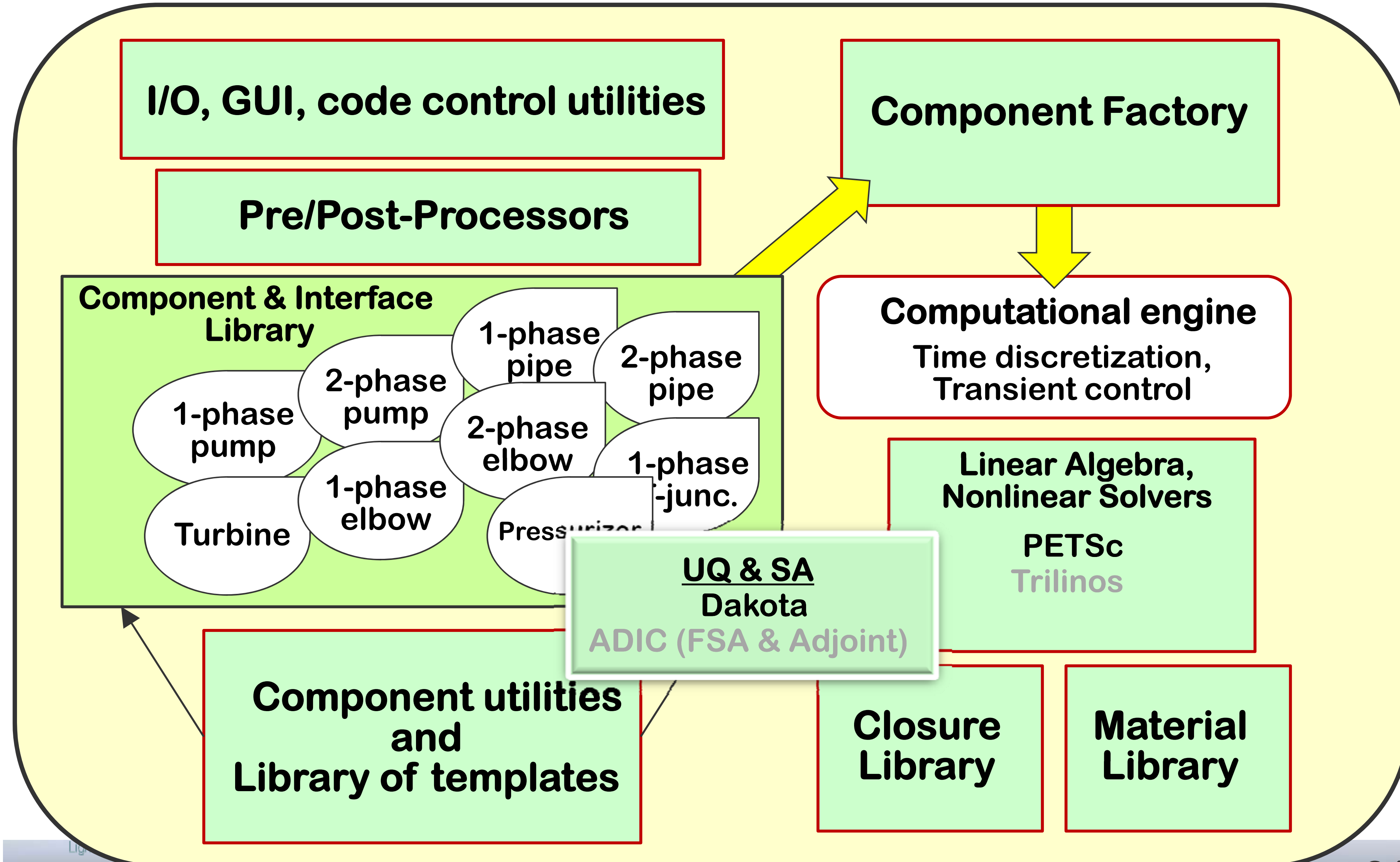
✓ Homogeneous Equilibrium (+Interfacial Slip) Model

❑ Two-fluid 6-equation hyperbolic 1-pressure (+interfacial pressure) model

❑ Two-fluid 7-equation hyperbolic 2-pressure model (DEM)

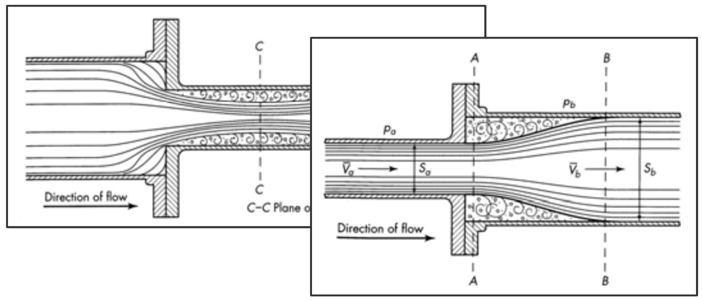
- “Born-assessed”, with sub-version control (Trac web-based), extensive verification and documentation (“ANT” Manual, Doxygen – html-based Manual), 3D visualization, GUI, regression testing

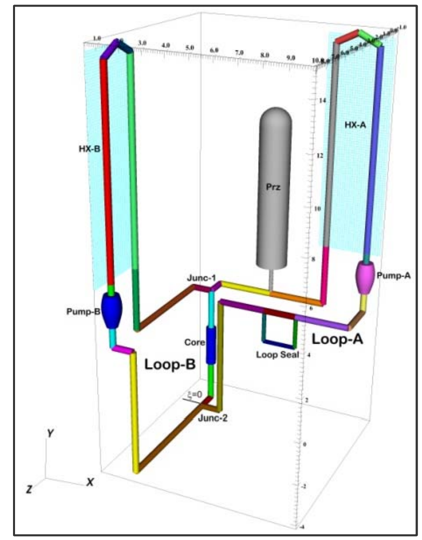
Version β-2: highlights



Whats new? (since 10.10)

- Two-phase modeling: (in progress)
- Junctions: Expansion/contractions, 3-pipe junctions





- Materials: FREESTEAM water property package
- Pressurizer: new realistic model is developed
- 3D FEM: in the process of testing

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